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Molten Metal Deposition (MMD) A356 and 6061 Heat Treatment, Tensile Properties, and Fracture

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Abstract

The mechanical properties of parts printed using Additec's Magneto-Hydrodynamic (MHD) MMD additive technology are critical to the adoption of the technology. Correspondingly, it is important to optimize the printing process to maximize the desired properties. In order to maximize the desired properties, it is necessary to understand the fracture behaviors. In this paper, the fracture behaviors of MHD MMD aluminum parts are investigated. The mechanical properties are also examined and the effect of heat treatment modifications on the output properties is studied for Al A356 (4008) and Al 6061. The findings of this study indicate that there is potential for modification at the heat treatment step that can allow for trading off of some mechanical properties to maximize others, although in the majority of cases we find the standard processes provide adequate mechanical properties, in line with ASM standards for the targeted materials.

Introduction

Additive Manufacturing (AM) describes a large array of technologies that share the commonality of a layer-by-layer building process. Using this layer-by-layer process, three-dimensional (3D) parts can be built directly from a CAD model without requiring additional tooling and machining. This presents many advantages over traditional manufacturing but only if the mechanical properties of the printed parts can match up to those made by traditional manufacturing.

The most widely used method of metal AM is Powder Bed Fusion, and the technology has been well developed. However, Powder Bed Fusion's largest drawback is the volatility of the powder used in printing. Molten Metal Deposition (MMD) is a newer technique that avoids this drawback by using wire feedstock to create a molten metal reservoir from which droplets are generated. These droplets are placed sequentially on a heated substrate as determined by predefined build rules and the CAD model in order to form layers and, eventually, the complete part.

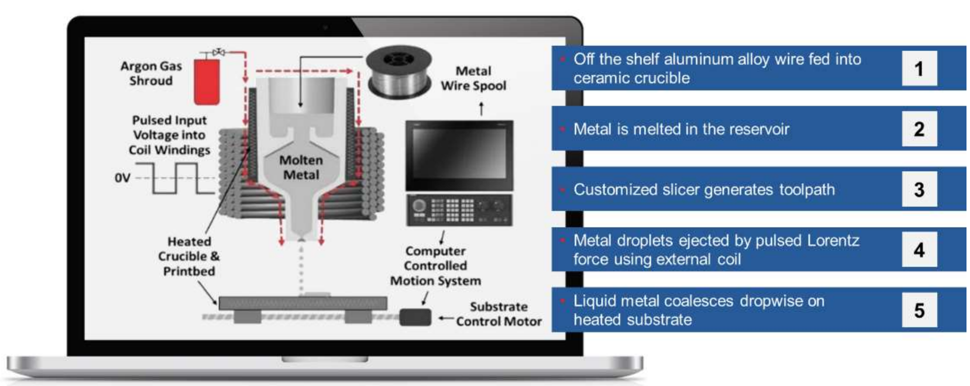

Figure 1: System Diagram of MHD MMD Printer

MMD printing, unlike PBF printing, does not require powder (expensive and volatile) as an input material. Additec's system currently utilizes a wire feed system, but rod- and pellet-feed systems are certainly possible. Additionally, it is straightforward to keep the alloy composition of the printed parts in line with the feed stock; minimal material is lost to evaporation or other waste processes, and so the printed part is the same alloy as the wire that entered the molten reservoir[1].

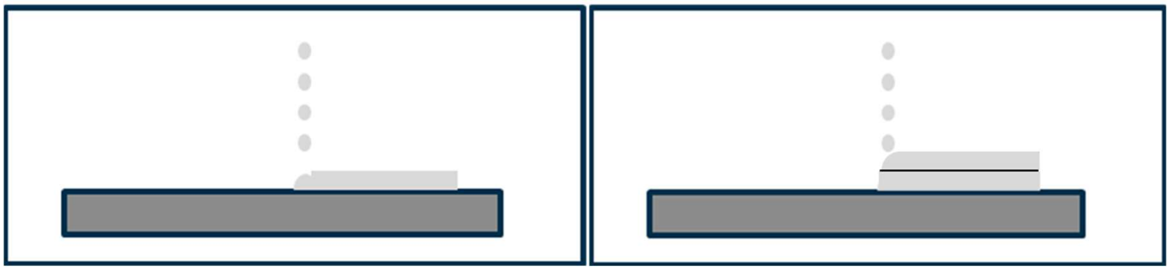

Figure 2: Left, drops are placed on heated substrate in quick succession, forming a layer. Right, drops are placed similarly, but on top of the previous layer.

It is useful to understand the build process of MMD printing before diving into a discussion of the fracture behaviors. Although there are several methods that may be used to generate droplets in MMD printing, the build process is similar across all of them. Droplets are initially placed one-by-one on a heated substrate and form together. Each droplet will rapidly cool after placement[2]; however, due to the high frequency of the drop placement, each subsequent drop will partially re-melt and bond with the previously placed drop prior to completely cooling. Once the first layer is completed, the subsequent layers will be printed similarly, but drops are now placed on the previous layers. There is significantly more time delay involved in this placement; in combination with the heat of the substrate, this is sufficient time for a thin oxide layer to form. Consequently, rather than the droplet-to-droplet metallic bond seen within a layer, between layers the part relies on a ceramic droplet-to-oxide bond, which impacts the mechanical properties. Understanding the causes of this and investigating methods of mitigation is part of the focus of this work.

As a newer technology, MMD has not reached the maturity level of older metal AM technologies. As such, there are more areas of the MMD process that need to be explored and understood to improve the capabilities. The focus of this investigation is on the material structure and mechanical properties of MMD printed parts. Additec's Magneto-Hydrodynamic (MHD) MMD process can jet multiple Al alloys, of which the focused alloys are A356 (4008) and 6061. For both alloys, the fracture behaviors are investigated to understand the mechanics of how mechanical failure occurs in MMD parts. Once the mechanisms are understood, the next step is to look at methods of amelioration, with the ultimate goal to be producing parts with mechanical properties on par with traditional methods, using ASM benchmarks as the measured goals.

Methodology

i. *Fracture Investigation*

To examine the fracture behavior, the Additec MMD system was used to print rectangular prisms. Initial work was done with Z-directional prisms, as this is the direction with greater difficulty. After the heat treatment process was optimized for the Z-direction, XY-direction bars were printed and put through the optimized process for validation. The testing was originally performed for Al A356 (Al 4008), then was repeated for Al 6061.

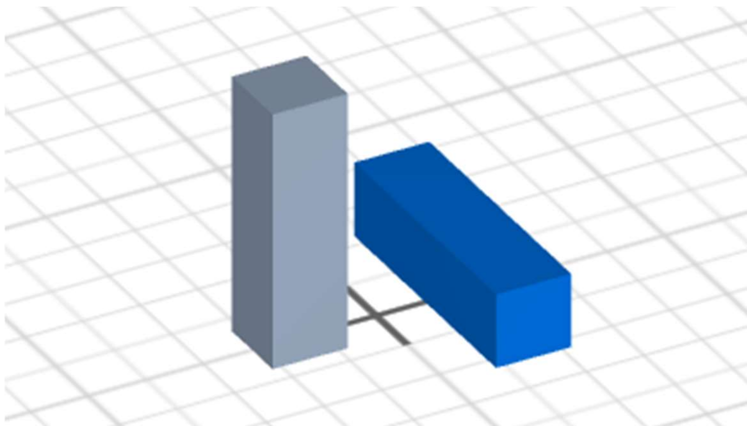

*Figure 3: Simplified orientation diagram. The left, grey bar will be pulled along the build's Z-direction and is used to check Z frac*ture. The *right, blue bar will be pulled along the build's XY direction and is used to check the XY fractures.*

After printing, the bars were removed from the build plate. They were heat treated using a T6 process (solution treatment followed by aging treatment) before being machined into dog-bone tensile bar shape. The resulting tensile bars were put through tensile testing using an MTS Criterion tensile tester. A Keyence profilometer was used to capture images and profile data of the fracture surfaces.

ii. Mechanical Properties Testing

To examine the mechanical properties of Additec's MMD aluminum, multiple tensile bars were prepared. As with the fracture investigation, the MMD system was used to print rectangular prisms in two alignments; additionally, to compensate for the variable of layer time, alternate geometries were printed that enabled multiple bars to be printed simultaneously. These were all put through appropriate heat treatment per AMS standard for their alloy and then machined to shape; for the alternate geometries, this first involved machining the larger geometry into multiple rectangular prisms before machining those prims into dog-bone tensile bars. The MTS Criterion tensile tester was used to collect the stress/strain curve data.

For modified solution treat testing, the same process was followed save that rather than the standard AMS heat treatment process, the temperature of the solution treat was used as a modifying variable. The duration of solution treatment remained constant (Al 4008: 4 hours. Al 6061: 1 hour.)

Results and Discussion

i. *Fracture Investigation*

The examination of the fracture patterns shows different fracture behavior corresponding with print direction. The fracture patterns along the XY-build direction are more ductile, with the fracture occurring within droplets rather than at droplet boundaries. In the Z-build direction, however, the fractures clearly are occurring at the layer boundaries. The droplet surfaces are clearly visible and identifiable at the fracture face.

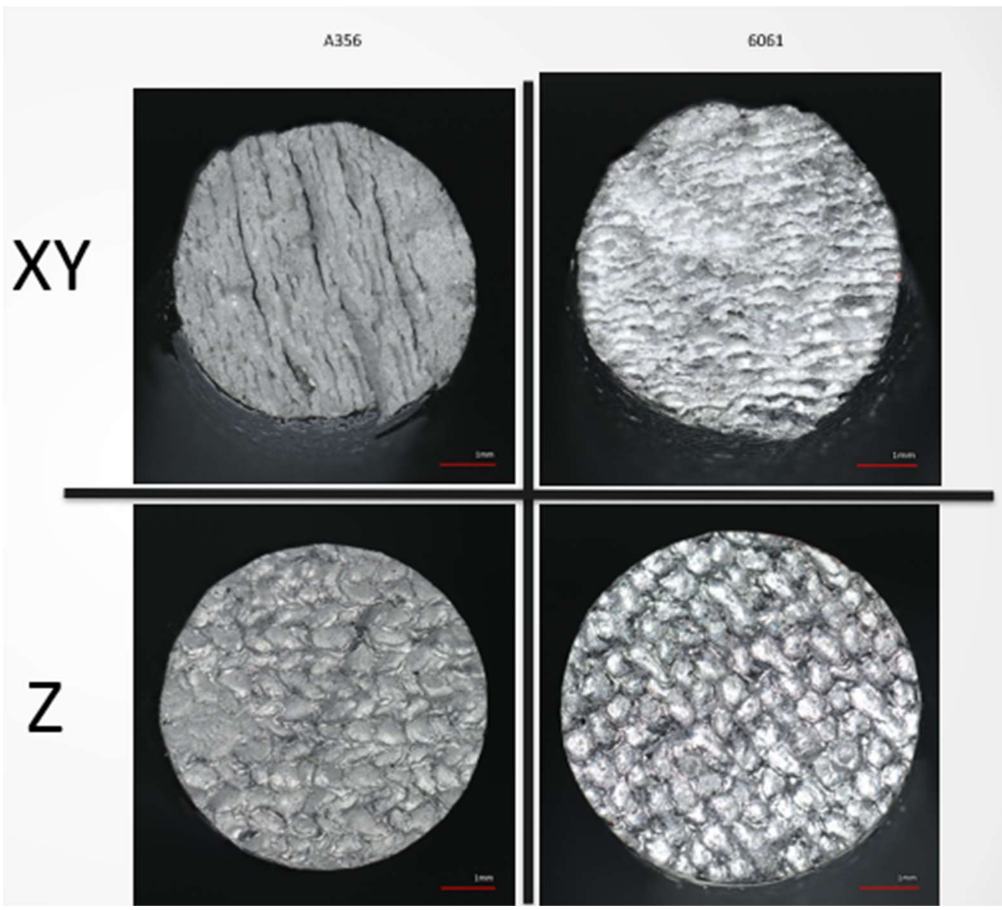

Figure 4: Top down view of fracture behavior for Al A356 and Al 6061 in the XY- and Z- build directions.

This holds true in both cases for Al A356 and Al 6061. In the XY-build direction, there is noticeable delamination in the Al A356 build, with fracture break patterns also propagating along layer lines. In the Al 6061, this is not the case, and the fracture follows a more arduous path, indicating greater ductility. Although not covered in this paper, previous work has shown that tensile coupons printed at an angle show similarity to the Z-direction prints, fracturing at layer boundaries, although typically through multiple layers rather than a singular layer. [2]

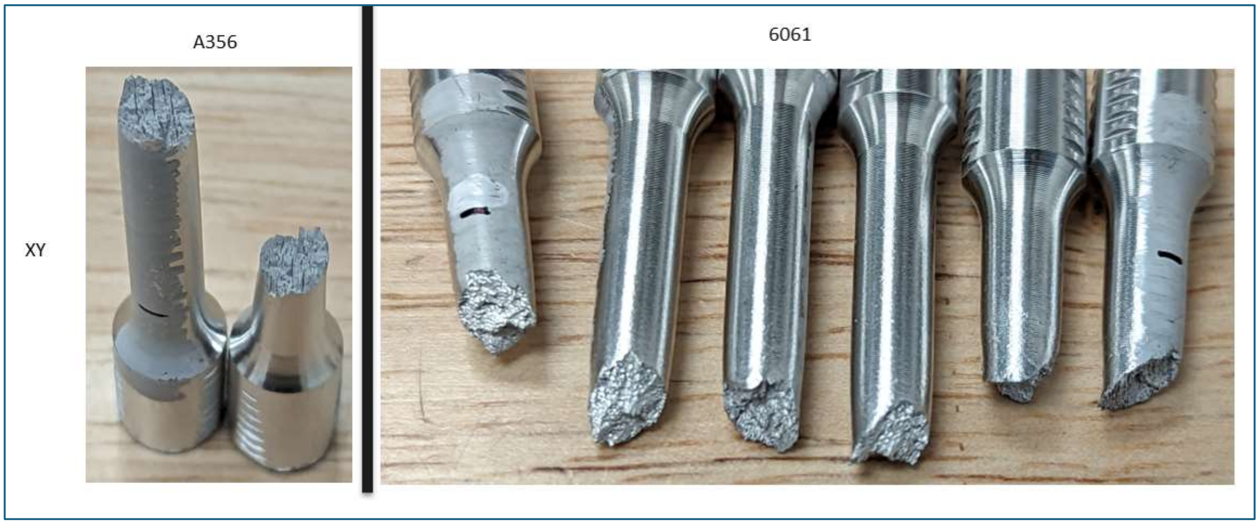

Figure 5: Left, Al A356 fracture behavior for the XY build direction. Delamination behavior is visible along layer lines. Right, Al 6061 fracture behavior for the XY- build direction. The fracture behavior does not show delamination and appears more ductile.

The fracture behavior is in line with pre-existing expectations based on the build structure of the MMD system. Due to the time spent at temperature between layers, a thin oxide layer is expected to form as the surface is exposed to atmosphere. Based on the fracture behavior, it can be deduced that the fracture occurs at the Al-AlMgO boundary in the Z-build direction, while in the XY-build direction the droplet-to-droplet bonding does not have a specific failure initiation point.

The Z-direction fracture behavior is consistent across both alloys being investigated, unlike the XY-direction fracture behavior. The Z-direction failure mode is dominated by the layer boundaries for both alloys. In the XY-direction, the different behavior of the Al 6061 alloy failures is interesting but no definite conclusions have been drawn as to the cause of the difference.

Figure 6: Left, Al A356 fracture behavior for the Z-build direction. The fracture occurs on the layer boundary. Right, Al 6061 fracture behavior for the Z-build direction. The behavior is very similar to the A356.

ii. *Mechanical Properties and Heat Treatment Modification*

a. Aluminum A356 (Al 4008)

Prior to this study, the mechanical properties of Al A356 printed using Additec's MMD process were already thoroughly investigated. For a baseline, a T6 heat treatment process was used, and the results were comparable to sand cast Al A356.

	Orientation	As Printed Average	T-6 Average
UTS (ksi)	XY	28	48
	Z	27	44
YS (ksi)	XY	13	34
	Z	13	33
Elongation (%)	XY	27	18
	Z	23	7

One thing of note is that the MMD printing process with ductility post-heat treatment, and therefore elongation, especially in the Z-direction. Although for A356 the results are adequate, for Al 6061 the elongation targets are more difficult to reach. It was proposed to modify the heat treatment process in order to adjust the final mechanical properties.

Additec's MMD process has a much larger build process window for quality A356 than for 6061, and additionally has been printing A356 successfully for a longer period of time. As a consequence, the initial investigation of heat treatment modification was done on A356 prints, with intent to apply the knowledge gained to Al 6061 parts subsequently.

The initial variable was chosen to be the temperature of the solution treat step. The baseline heat treatment process for Additec's A356 parts is solution treat at 538° C for four hours, followed by an age hardening process at 154° C for three hours. For modification, the lowest solution treat temperature was chosen to be 480° C, which was increased for subsequent parts in 4° C intervals until investigation of the fracture surfaces showed full transition to the delamination fracture mode typical of Additec's MMD Z-direction fractures. Additional data points were taken at the nominal 538° C, as well as a top-of-range 550° C as a check on the higher end of the range. The resulting mechanical properties data, in combination with the fracture investigation at each stage, revealed several things about how the build behavior influences the mechanical properties of the MMD parts.

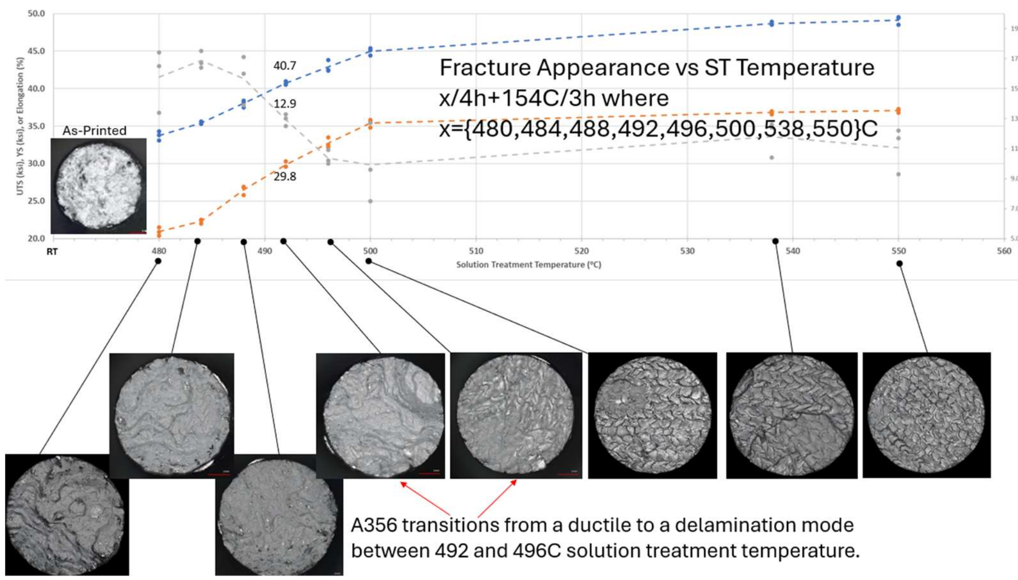

Figure 7: A356 Solution Treat Temperature Variation. The graph shows UTS, YS, and Elongation % results at each setpoint as well as corresponding fracture behavior.

The solution treat temperature variation showed that the delamination fracture mode occured only at high enough solution treat temperatures, and below that the fracture mode was more ductile. Additionally, rather than occurring at layer boundaries, it occured within droplets. At the same temperature point as the fracture transition, the YS and UTS gains leveled off. The drop off of the elongation % also leveled off at around the same point. The results showed that there was indeed the possibility of increasing the elongation %, although at a cost to other mechanical properties. For Al A356, which meets mechanical property targets with a nominal T6 procedure, this is interesting but not necessarily required; however, it was useful as a starting point for Al 6061.

b. Aluminum 6061

ST Temp	YS	Elongation %	UTS
500	35800	5.5	39900
	35700	4.6	39700
	36100	6.6	40100
	35100	5.2	39100
530	38400	4	41050
	38800	4.3	41900
	38950	5.1	42800
543	47000	1.6	42250
	41100	1.7	42900
	41100	2.5	43350
556	41950	0.6	37100
	42200	1.1	42000
	42200	1.5	43000

Figure 8: Mechanical Properties Data for Z-direction Al 6061 on Additec MMD system at several solution treat temperatures.

The data collected for the mechanical properties of MMD Al 6061 parts was done using a T6 heat treatment process with solution treat temperatures at 500° C, 530° C, 543° C and 556° C. The initial focus was on properties in the Z-direction as the limitations of the build process typically keep the Z-direction properties lower than the XY-direction properties. After the initial temperature sweep, 500° C was chosen for additional data collection including XY-direction properties.

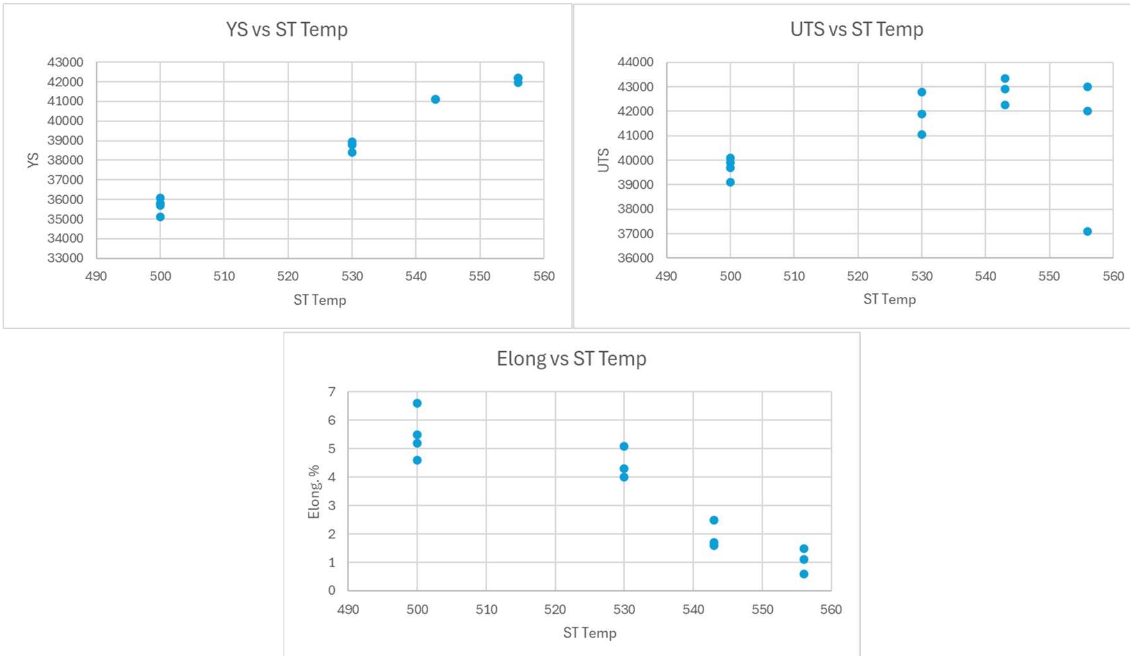

Figure 9: YS, UTS, and Elongation % of Z-direction 6061 vs Solution Treat Temperature

The behavior seen when examining these results is very similar to that observed in Al A356; as the solution treat temperature increases, the YS and UTS values begin to level off, while the elongation percentage falls with increased temperature until it also begins to level off. 530° C is the expected solution treat temperature and is approximately where the leveling off begins. 500° C is somewhere before the leveling off occurs, but the results for UTS and YS are still achieving ASM targets for to extruded 6061 (38 KSI for UTS and 35 KSI for YS) while the elongation percentage is slightly improved over the 530° C temperature process.

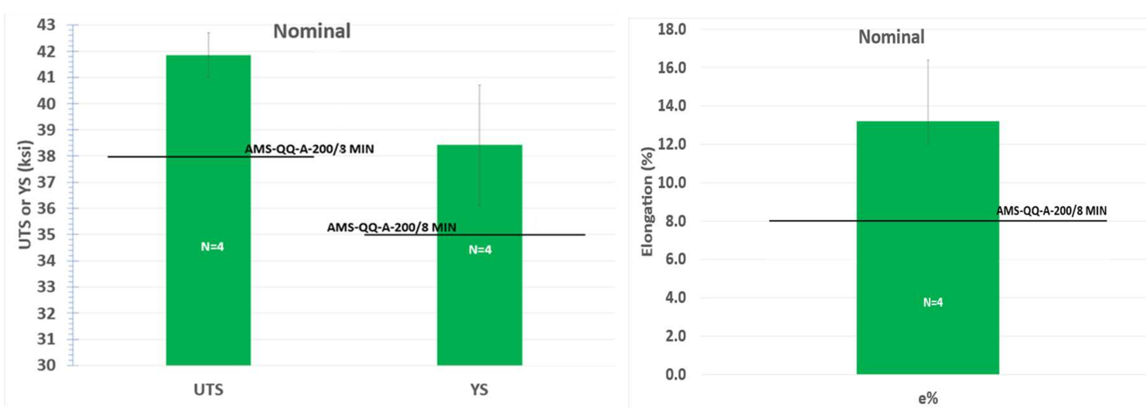

Figure 10: XY mechanical properties of printed 6061, using a modified T6 solution treat at 500 C. AMS targets for extruded 6061 are marked.

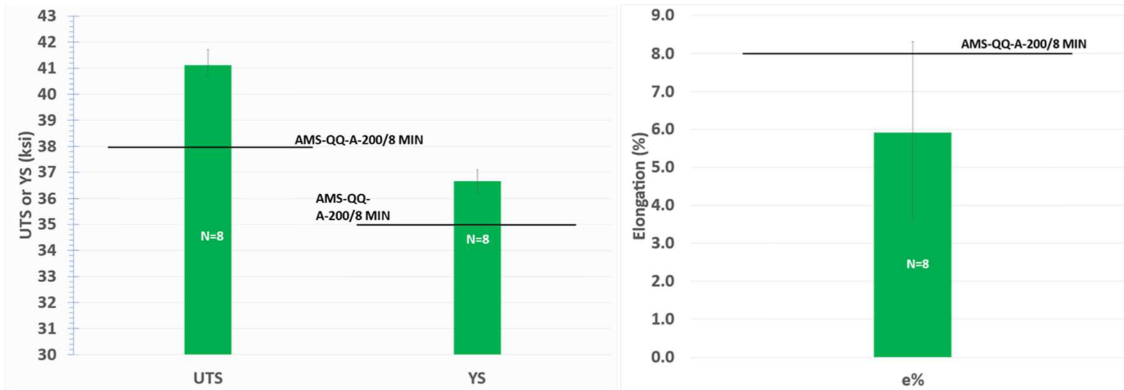

Figure 11: Z Mechanical properties of printed 6061, using a modified T6 solution treat at 500 C. AMS targets for extruded 6061 are marked.

Despite the application of the lower solution treat temperature, the elongation percentage of the Z-direction build is still lower than the desired performance. However, there is indeed an improvement of approximately 2%. This comes at a cost of nearly 3 ksi in both UTS and YS; they both remain ahead of the AMS minimums, but are closer than would be preferred.

Conclusion

This study examined the fracture behavior and mechanical properties of Additec's MMD aluminum parts, both A356 and 6061. It additionally looked at the same properties when incorporating modifications to the heat treatment process to attempt to optimize the mechanical properties. The following conclusions were reached:

i. The different fracture behavior and mechanical properties between the XY- and Z-build directions is directly related to the formation of oxide between layers.

ii. With the sole exception of Z- build direction elongation percentage, Additec's MMD aluminum parts achieve ASM standards for their alloy compositions.

iii. It is possible to modify the solution treat process in order to adjust the resulting mechanical properties, but improving the elongation comes at the cost of lower YS and UTS.

iv. There is likely further optimization that can be done on the heat treatment process to further modify the final properties.

References

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